NOISE BUDGET FOR THE X-RAY MICROCALORIMETER SPECTROMETER (XMS) CORE ARRAY

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1 INTRODUCTION

1.1 Purpose

The purpose of this document is to present and archive the noise budget for the XMS detector, in order, at this stage in mission planning, to learn the scale of the requirements placed on the other instrument subsystems.

1.2 Scope

This document mainly concerns the core array, specifically the baseline version that emerged from the trade studies associated with the ESA Phase A study report. Qualitative extension to the Hydra approach to the outer array is included at the end.

2 REVISION HISTORY

This is the first release, but makes official XMS_noise_budget_v2.2.doc and XMS_noise_budget_v2.2.xls.

3 REFERENCE DOCUMENTATION

GSFC-XMS-RP-2010-006 (SRON)– XMS Detector Trade Study

SRON-XMS-RP-2010-007 (SRON) – XMS Read-out Trade Study

IXO_MUX_NIST_GSFC_v1.pdf (NIST, Doriese) – preliminary TDM optimization

IXO_XMS_ref_tanh-GLbetaV2-0.pxp – Igor experiment file and electronic notebook with details of the simulation and parameterization

4 NOISE BUDGET FOR THE CORE ARRAY

4.1 Parameters of the model

The following parameters define a pixel of the reference design (see GSFC-XMS-RP-2010-006 and IXO_MUX_NIST_GSFC_v1.pdf) that was used to produce the noise budget.

T_c = 90 mK
T_{bath} = 50 mK
C = 0.8 pJ/K
n=3
α_I = 75
β_I = 1.25
R = 1 mΩ
G = 200 pW/K

The values for C, G, R, T_c, α_I , and β_I apply to the quiescent bias point.

4.2 Approach

In the reference model, the value of R_s and L, the shunt resistor and shaping inductance, were left as design choices for the read-out. For the purpose of deriving the noise budget, I have fixed these at the values from Randy Doriese's preliminary optimization for TDM (IXO_MUX_NIST_GSFC_v1.pdf):

$R_s = 0.24$ mΩ
L = 159.4 nH
.

Instead of separating the contributions of intrinsic detector noise, multiplexer noise, and choice of record length, I assigned a single allocation to the combined effects of these terms. The reasoning behind this is that the choice of how the TES is biased affects the needed record length and the choice of coupling into the multiplexer, which in turn determines the input-referred SQUID noise. Thus, these terms need to be optimized simultaneously and systematically. For this paper, I am assuming that the multiplexer noise includes all of the noise in the amplifier chain. I have given separate allocations to several other terms from the detector system electronics. These are the bias noise, the bias stability, and the gain stability. In the future, it would be appropriate to include the bias noise in the detector-plus-multiplexer model, since it is a noise term that enters the model in the same way as the shunt resistor's Johnson noise. The stability terms, however, should be tracked separately since they don't add noise in the signal band, but instead cause the gain to vary.

4.3 Gain drift and stability

There are several terms in the noise budget that act by changing the detector gain from the calibration conditions. The relevant time scale for these terms is longer than a record length, but shorter than the integration time needed for adequate statistics from the onboard gain-tracking calibration source. I have assumed the latter value is 10 minutes.

One approach to allocating limits to the contributions of the individual gain terms is to consider them as random fluctuations over the frequencies corresponding to the relevant time scales. In that approach, a determination of gain sensitivity such as eV/μK and a noise allocation in units of eV (FWHM) are combined to impose a limit on the RMS of the fluctuations. Most gain terms, however, are expected to change very slowly, such as from temperature variation in the electronics boxes. If the gain change can be approximated as linear on time scales much longer than the calibration source integration time, then the gain can be corrected down to much shorter time scales than the integration time. For this noise budget, I have taken an intermediate approach. I have assumed that most of the gain terms are indeed slow, but that existence of several such terms with different time scales limits our ability to interpolate. I have assumed that each term drifts linearly on the time scale of 10 minutes, and thus contributes an RMS broadening equivalent to the standard deviation associated with a linear drift though a central reference point. (The RMS contribution of a drift from –A/2 to A/2 is A/sqrt(12).) I have assumed that the different drift terms are uncorrelated, and thus add in quadrature. I have referenced all gain changes to 6 keV, the highest energy at which 2.5 eV resolution is required.

A small signal model is not sufficient to determine gain changes that result from changes in the detector operating point; it is necessary to simulate pulses. I have used a simple $R(T, T_c(I))$ function to describe the superconducting transition, where $T_c(I)$ depends on β_I via the Ginzburg-Landau relationship between T_c and I. It is not meant to be correct in the details, but only in the general scale of the non-linearity. In this model, the bias point is 12.5% of a normal resistance value of 8 mΩ. With the reference-model parameters fixed at that point, α_I , and β_I are 44.05 and 0.47, respectively, at the constant bias needed to operate at 50%. The α_I is comparable to values measured at 50% for several GSFC TES that are similar to the reference model at 12.5%, but a typically observed value for β_I would be around 0.1 at 50%. Ultimately, the model should use a measured R(T,I) surface.

In order to include the effect of pulse shape on the gain change, I generated an optimal filter based on a 600 eV pulse and the model noise. I applied this filter to each pulse generated as the parameter under investigation was varied, leaving all other parameters fixed. In this way I modeled the gain change that would be seen in the processed data for a fixed optimal filter if one of the model parameters, such as the bias voltage, were to drift.

4.4 Terms in the XMS noise budget

The terms in the noise budget, tabulated in Section 4.5, are defined as follows.

excess broadening: This term is an allocation for the allowable degradation (at 6 keV) for position dependence and thermalization variation in the absorber. An allocation of 0.3 eV is equivalent to getting 2.3 eV resolution on the line and 2.28 eV resolution on the baseline.

sub-mm photon noise: The design of the blocking filters and feedthroughs must limit radiation from the next higher temperature shield that can impinge on the TES array. I have imposed a rough limit on this radiation by assuming that it is all from 0.3 meV photons that produce optimally filtered shots in the detector of the shape in Fig. 1, approximated as a two-sided exponential decay with time constant of 0.267 ms. A limit of 0.3 eV noise from such shots corresponds to a limit on their absorbed power of 32 fW per pixel.

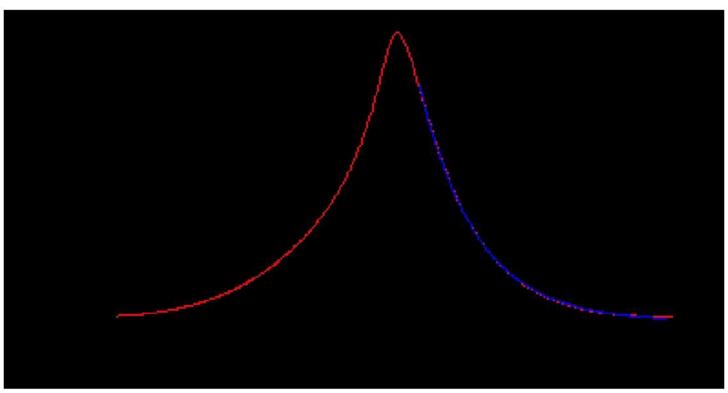

Fig. 1: Optimally filtered pulse shape. The decay time is 0.267 ms.

thermal crosstalk and frame hits: This term is an allocation for the allowable degradation from photons and cosmic rays depositing energy in the thick silicon frame of the array, as well as thermal crosstalk if it is not feasible to correct for thermal crosstalk by using the measured primary pulses. This limit imposes constraints on the heat sinking of the array.

electrical crosstalk: This term is an allocation for electrical crosstalk from inductive coupling or from non-ideal effects in the multiplexer.

gain stability: The SXS stability estimate presumes a temperature coefficient of 200 ppm/°C. If we presume that it will be easier to control the temperature of the electronics boxes at L2 than in low-earth orbit, we can realistically use a lower value for the bias drift for IXO. I have specified the requirement on the stability of the overall gain of the read-out electronics as <0.0025% in 10 minutes. For 6 keV events, the non-linearity (see Fig. 2) causes a 0.01% change in gain to map into a 0.012% change in assigned energy. An allocation of 0.0025% thus results in 0.12 eV FWHM of noise from gain instability. Note that this factor for the non-linearity of the gain scale needs to be applied to the effect of all gain terms. For example, if a change in ADR temperature results in a fractional change in filtered pulse height, x, then the effect in eV at 6 keV is not 6000x, but 1.2*6000x, because the calibration curve will map the change in pulse height to a larger change in energy.

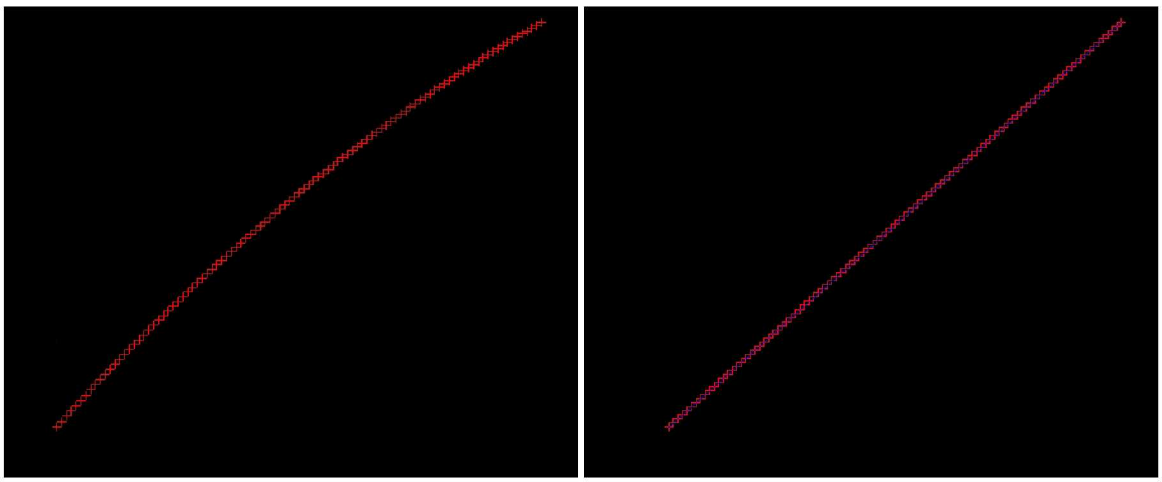

Fig. 2: Simulated gain function for optimally filtered pulses from the reference detector.

ADR control: The model predicts a gain change at 6 keV of 0.115 eV/μK when the non-linearity of the calibration curve is considered. I have allowed this gain term to have a random component of 1 μK RMS as well as a drift of <4 μK over 10 minutes, for a total degradation of 0.4 eV FWHM.

bias noise: Voltage noise at the top of the bias resistor (presumed to be 2.4 kΩ) is attenuated by the divider formed by that resistance and the shunt resistor. I adopted a value of 60 nV/sqrt(Hz), which is the expected bias noise at the supply for the Astro-H/SXS calorimeter. The resulting contribution to the noise budget is only 0.1 eV, almost negligible.

bias stability: Bias stability, on the other hand, is potentially a much more significant term. For this XMS reference TES, a 0.01% change in detector bias causes a 0.016% change in filtered pulse height, and a 0.020% change in inferred energy. In this noise budget, I have presumed <0.0025% bias drift in 10 minutes, which results in a 0.2 eV FWHM from bias instability.

environmental magnetic field stability: This term is not much more than a placeholder at this time, though it is based on one measurement of the change in pulse height with changes in applied field near zero field.

margin: This would cover a small omission or a too optimistic assessment in some of the other terms.

4.5 Noise budget table

	eV FWHM		
intrinsic + MUX + record size	**2.3**		
	allocation	**in units measured**	**comments**
	(eV)		
detector system budget			
excess broadening	0.3	0.3 eV	
sub-mm photon noise	0.3	32 fW of 0.3 meV photons	peak of 1.3K blackbody
thermal crosstalk/frame hits	0.4	0.4 eV	
electrical crosstalk	0.4	0.4 eV	
other subsystems			
ADR control	0.4	1 uK RMS and 4 uK drift	drift over calibration time scale of ~ 10 min.
bias noise (at 2.4 kOhm bias R)	0.1	60 nV/sqrt(Hz)	is 60 fV/sqrt(Hz) at shunt resistor
bias stability	0.2	0.0025% drift in 10 minutes	N% change causes 2.0N% change in E at 6 keV
gain stability	0.12	0.0025% drift in 10 minutes	N% change causes 1.2N% change in E at 6 keV
environmental B field stability	0.4	~40 pT RMS or ~140 pT drift	based on gain vs. field measurement
RESERVED MARGIN	0.3	0.3 eV	sum of other small terms not explicitly considered
RSS of base and noise	**2.50**		

model and electronic notebook contained in Igor file IXO_XMS_ref_tanh-GLbetaV2-0.pxp

5 CONSIDERATIONS FOR THE OUTER ARRAY

5.1 Approach

Rather than repeat the study for a model for the outer array, I chose to estimate the impact of the allocations set by the core array on the outer array. The reference design for the outer array, a 4-pixel Hydra, can be found in GSFC-XMS-RP-2010-006. Key differences from the core array used for scaling the noise budget are the lower operating temperature (75 mK), the higher heat capacity (> 10 times higher), and the higher thermal conductance from the TES to the frame (to meet the count rate requirements of the outer array). The terms of the noise budget were added in quadrature to 9.5 eV, the average Hydra resolution with the effects of the record length choice and multiplexer noise already included, resulting in 11 eV.

5.2 Differences in sensitivity

In many respects, the outer array is more vulnerable to the noise sources of the noise budget than the core array, but the impact is minimal because of the worse starting resolution. The resulting noise budget is meant as a qualitative guide. The fact that the predicted resolution is 11 eV, slightly worse than the required 10 eV, should not be taken as the final answer.

excess broadening: The excess broadening term is increased to account for the larger extent of the absorbers and the higher thermal conductance from the TES to the heat sink.

sub-mm photon noise: The area is increased by a factor of 16, so the noise scales by a factor of 4.

thermal crosstalk and frame hits: This term has been scaled up substantially to account for the diminished feedback (from the lower T_c) and the higher conductance.

gain stability: Gain is assumed to be linear because of the larger heat capacity.

ADR control: In the core array model, if T_c is reduced to 70 mK, the sensitivity to temperature fluctuations increases by nearly a factor of 3. Thus, I estimated that the Hydra sensitivity to temperature variation is 2.5 times that of the core array.

bias noise: I assumed the impact would scale with the resolution, that is, by the same factor as the noise terms already considered.

bias stability: Bias stability was presumed to scale by the same factor as temperature stability.

5.3 Noise budget table for the outer array

	eV FWHM		
intrinsic + MUX + record size	**9.5**	average within 4-pixel Hydra	
	allocation	**in units measured**	**how scaled from core array**
	(eV)		
detector system budget			
excess broadening	2	2 eV	larger absorbers, lower T (diffusivity)
sub-mm photon noise	1.2	512 fW of 0.3 meV photons	16x the area
thermal crosstalk/frame hits	5	5 eV	larger pixel G, less feedback
electrical crosstalk	0.4	0.4 eV	keep same
other subsystems			
ADR control	1	1 uK RMS and 4 uK drift	x2.5 greater sensitivity from lower Tc
bias noise (at 2.4 kOhm bias R)	0.4	60 nV/sqrt(Hz)	scale with resolution
bias stability	0.5	0.0025% drift in 10 minutes	x2.5 greater sensitivity from lower Tc
gain stability	0.1	0.0025% drift in 10 minutes	larger heat capacity, assume linear
environmental B field stability	0.4	~40 pT RMS or ~140 pT drift	keep same
RESERVED MARGIN			
RSS of base and noise	**11.1**		